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RIE-TEXTURING OF INDUSTRIAL MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT

We developed a maskless plasma texturing technique for multicrystalline Si (mc-Si) cells using Reactive Ion Etching (RIE) that results in higher cell performance than that of standard untextured cells. Elimination of plasma damage has been achieved while keeping front reflectance to low levels. Internal quantum efficiencies higher than those on planar and wet-textured cells have been obtained, boosting cell currents and efficiencies by up to 6% on tricrystalline Si cells.

INTRODUCTION

The quality of low-cost multicrystalline-silicon (mc-Si) has increased to the point that its cell performance is close to that of single crystal (c-Si) cells, with the major difference resulting from the inability to texture mc-Si affordably. A low-cost, large-area, random, maskless texturing scheme independent of crystal orientation is expected to significantly impact the cost and performance of mc-Si photovoltaic technology. Web and ribbon-Si technologies also produce high-quality Si wafers, but as yet have not been able to introduce cost-effective cell texturing, which would provide a significant boost in their performance.

The innovation represented by this process lies in its ability to texture entire large-area mc-Si wafers at once. Other novel, wet-chemical approaches that work on some mc-Si materials are not effective on shiny web or ribbon materials because of their lack of nucleation sites. Because the RIE-texturing process removes several microns of material, it may also be used as a replacement for saw-damage removal etching, thereby simplifying and reducing the cost of the wafer preparation process.

Tri-crystalline Si wafers could produce cells with 5% higher yields than mono-Si due to their increased strength, but their use would require a replacement of the low-cost anisotropic wet texturing that works well only on single crystalline Si. The use of stronger wafers with improved light-trapping properties could allow thinner cells to be fabricated, thereby increasing the number of wafers produced per ingot by 60% and markedly reducing cell costs.

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Other researchers reported the development of an RIE-texturing process using Cl_2 gas, which textures many wafers per batch, making it attractive for mass-production [1]. Using this process, they have produced a 17.1% efficient 225-cm^2 mc-Si cell, which is the highest efficiency mc-Si cell of its size ever reported. This shows that RIE texturing can be done without causing performance-limiting damage to Si cells. In this paper, we will discuss an RIE-texturing process that avoids the use of toxic and corrosive Cl_2 gas.

EXPERIMENTAL PROCEDURE

We developed several metal-catalyst assisted RIE-texturing techniques using SF_6/O_2 plasma chemistry in a Plasma-Therm 790 reactor. The cathode in the plasma chamber is constructed from graphite while the chamber walls and anode are made of aluminum. The textured surfaces exhibit reflectance of between 1 and 5 % for wavelengths below 1 µm without the benefit of anti-reflection films [2]. We investigated several texturing processes for different industrial mc-Si wafers to determine which produced the highest cell performance for various commercial fabrication sequences. We studied how to remove the plasma-induced contamination and surface damage without removing the benefits of the texture.

Previous work had shown that up to a 7% relative improvement in cell efficiency was obtained when two different RIE-texture processes were applied to groups of mc-Si wafers from BP Solar and compared with cells using planar control wafers from the same ingot [3]. In this paper, we will describe how these same two RIE-texture processes were applied to groups of tricrystalline (tri-c Si) wafers from Shell Solar. These groups were processed identically with two other groups of control wafers, one which received their standard alkaline wet-texture process, and one which remained planar. Then all wafers were processed through their industrial cell production line using standard process schedules.

EXPERIMENTAL RESULTS

Shell Solar

The results of the initial experiment are shown in Table 1. Both of the RIE-textured cell groups outperformed the planar controls, especially the one using the conditioned texture. As Figure 1 shows, the improvement due to the conditioned texture is statistically significant.

Table 1. Average and standard deviation of illuminated IV parameters for 4 groups of 102-cm^2 tri-crystalline cells processed at Shell.

Front Surface Condition	Eff	V_{oc}	J_{sc}	FF
	%	mV	mA/cm^2	%
CONDITIONED TEXTURE	**11.3**	**573**	**27.5**	**72**
Std Dev.	**0.3**	**4**	**0.4**	**1**
Ti-ASSISTED	**10.9**	**566**	**26.8**	**72**
Std Dev.	**0.4**	**6**	**0.7**	**1**
PLANAR	**10.7**	**565**	**26.9**	**71**
Std Dev.	**0.4**	**5**	**0.5**	**1**
WET-TEXTURED	**10.5**	**579**	**25.9**	**70**
Std Dev.	**0.7**	**10**	**0.9**	**3**

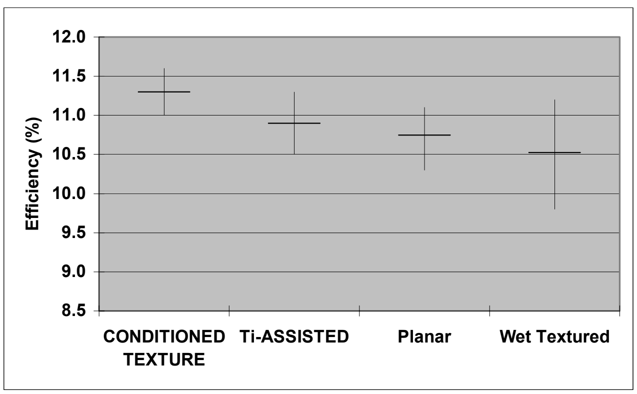


Figure 1. Average efficiency ± standard deviation for each of the 4 groups of cells.

Both groups of RIE-textured cells performed better than the planar cells, while the wet textured cells actually performed worse on average and had a higher degree of variability. To understand this, we performed Internal Quantum Efficiency (IQE) measurements on representative cells from each group. Results are shown in Figure 2.

The IQE curves show that the RIE-textured cell has superior long-wavelength response compared to the planar cell, probably due to the oblique coupling of light into the cell, which increases carrier collection efficiency and promotes light trapping. However, the condition-textured cell does show a slight reduction in blue response, most likely due to residual RIE surface damage, even though an RCA-clean and nitric/HF damage removal etch (DRE) were performed after texturing. The solar-weighted reflectance of the RIE-textured cell is lower at 12.4%, compared to 13.3% for the planar cell and 13.8% for the wet-textured cell.

In contrast, the wet-textured cell shows a sharp decrease in long-wavelength response, possibly due to bulk defects introduced by subjecting the textured tri-c surface to subsequent high-temperature steps. In addition, the wet-

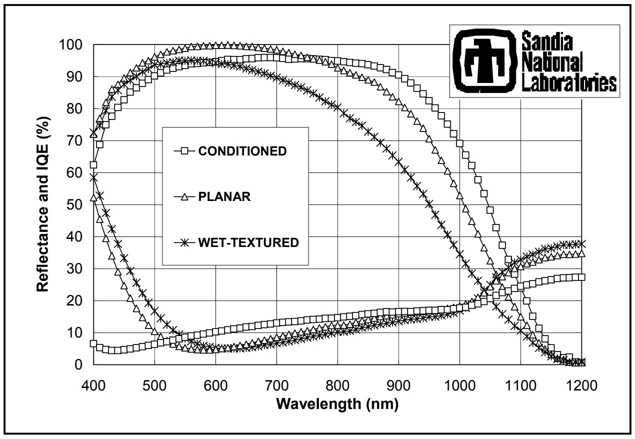


Figure 2. IQE and hemispherical reflectance of 3 tri-c Si cells with RIE-textured (conditioned texture), planar, or wet-textured front surfaces. All cells had otherwise identical processing, including single layer antireflection coating.

texture actually appears to increase the surface reflectance somewhat. A photograph of the four types of cells compared in this experiment is shown in Figure 3.

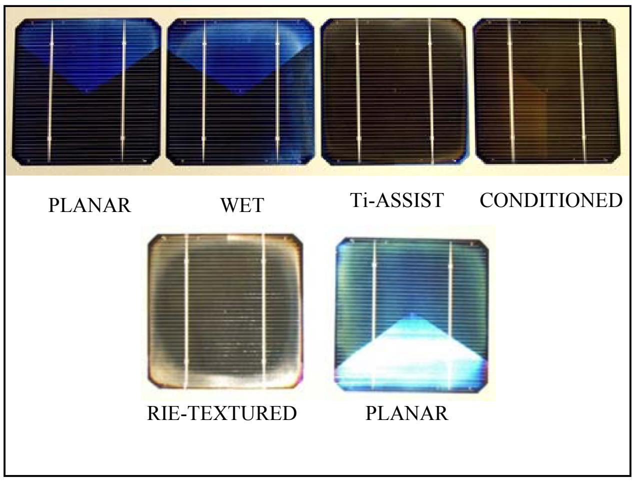


Figure 3. Top Row: Side-by-side photographs of cells from each group in experiment. Bottom Row: Conditioned and planar cells under high intensity light.

BP Solar

Previous work showed that an efficiency improvement of 2.5% could be obtained on RIE-textured BP Solar cells processed on their commercial production line [2]. We next studied whether the costly RCA-clean process was required for this performance improvement. We investigated cell response with and without an RCA clean, while using the identical conditioned texturing and nitric DRE processes. Results of this experiment are summarized in Table 2. We notice that incorporation of the RCA clean leads to a slight performance improvement relative to the no-RCA process, but the effect is statistically insignificant.

Table 2. Average illuminated IV parameters for 3 groups of 130-cm^2 mc-Si cells processed at BP Solar.

Cell Process	Eff (%)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)
Controls	12.5	29.0	582	74.0
RCA	12.3	28.8	578	73.7
No-RCA	12.2	28.9	577	73.2

The cell results in table 2 show that even with inclusion of the RCA clean and nitric DRE processes, the textured cell performance is still lower than that of the controls. Perhaps the nitric DRE process is not as effective on mc-Si surfaces as it was on tri-c Si. We therefore investigated alkaline-based DRE treatments. The results of the best alkaline-based DRE cells without RCA clean are summarized in Table 3. Since the wafers in this group were from the same material as those in table-2, both planar and nitric DRE results from Table 2 are included for comparison.

Table-3: Solar cell performance using different DRE treatments. No RCA clean was used after texturing.

Cell Process	Eff (%)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)
Controls	12.48	28.99	582	74.0
Nitric DRE	12.19	28.86	577	73.2
Alkaline DRE	12.59	29.28	580	74.1

This demonstrates for the first time superiority of RIE-textured cells over planar controls without using the expensive RCA clean and nitric/HF DRE processes. Even though the efficiency and J_{SC} enhancements of the alkaline DRE process are rather modest at about 1.0 %, they suggest that a larger performance boost could be realized through optimization of the DRE and RIE-texture processes.

Figure 4 shows pictures of 130-cm^2 RIE textured cells with nitric/HF DRE treatments compared to a planar cell. The corner regions and areas near the edges are either planar or have yellowish texture. This non-black area typically covers 10-15-cm^2 of the 130-cm^2 cell area and negatively impacts cell performance. Improvement of the texture uniformity should significantly improve textured cell performance.

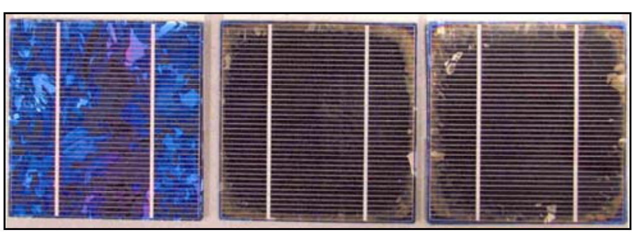
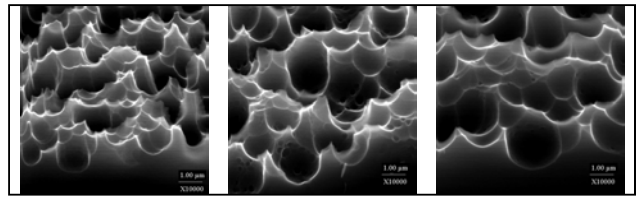


Figure 4. Side-by-side photograph of BP Solar cells. Left cell is planar, center and right cells are RIE-textured with nitric/HF DRE. All have commercial single layer ARC.

We have also examined the texture microstructure using scanning electron microscopy (SEM) following acid and alkaline-based DRE treatments. Figure 5 shows surface morphology after nitric acid DRE treatments of 20, 40 and 60 seconds. The effect of the DRE treatments is removal of all the nanoscale features even at the shortest duration of 20 sec. As etch times increase, only the largest feature dimensions survive, leaving structures with average dimensions in the 1-2 μm range. At the longest (60 sec) etch time, almost all of the sub-μm features are removed, leaving features with spacing in the 1-3 μm range.



(a) (b) (c)

Figure 5. SEM micrographs of mc-Si surfaces after conditioned texture and **nitric/HF** DRE treatments of (a) 20 sec, (b) 40 sec, and (c) 60 sec.

We evaluated the absolute spectral reflectances of cells subjected to nitric DRE treatments of increasing duration. Figure 6 shows hemispherical reflectance measurements of three cells labeled a3, b2, and c2, as well as from a planar cell. All the solar cells had anti-reflection nitride films.

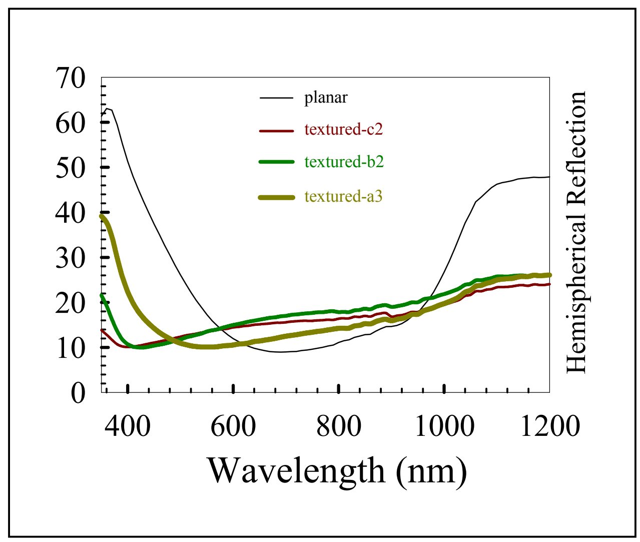
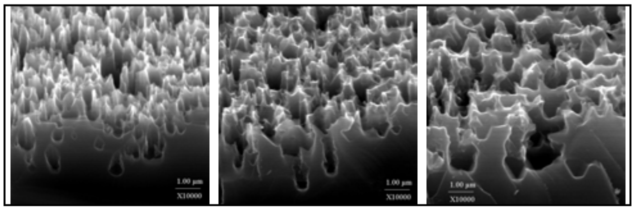


Figure 6. Absolute hemispherical spectral reflectance measurements of 4 BP Solar cells, including reflectance of gridlines. Cell c2 corresponds to Fig. 5(a), b2 corresponds to 5(b), and a3 corresponds to 5(c).

Increasing the nitric/HF DRE time increases the reflectance at short wavelengths due to removal of sub-μm size features. However, lower reflectance in the important mid-solar wavelengths are obtained with the 60 sec DRE.

In comparison, Figure 7 shows surface morphology after alkaline DRE treatments of 20, 40 and 60 seconds. In contrast with the results of nitric/HF etching, alkaline etching retains most of the fine structure. At 20 sec etch time, surfaces are almost identical to as-fabricated RIE surfaces except for removal of sub-50 nm features. At 40 sec etch, the feature distribution is not that much different than that of the 20 sec DRE process. At 60 sec etch, almost all sub-μm features have been etched away, leaving an average spacing of about 1.0 μm and feature dimensions of 0.5 to 1.0 μm.



(a) (b) (c)

Figure 7. SEM micrographs of mc-Si surfaces after conditioned texture and **alkaline** DRE treatments of (a) 20 sec, (b) 40 sec, and (c) 60 sec.

Ebara Solar

We were successful in developing an RIE-texturing process that produced low reflectance surfaces on shiny web-Si materials from Ebara Solar. Reflectance curves from two textured web blanks and a co-processed FZ wafer are compared with that of a planar web wafer in Figure 8.

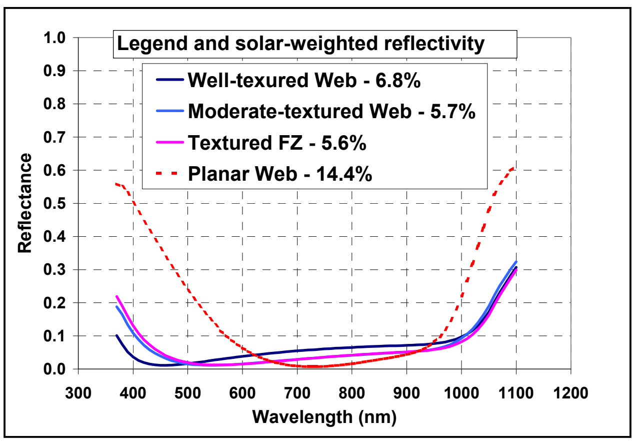


Figure 8. Surface Reflectivity with SiNx AR Coating of RIE Textured Cells (before grid metallization).

Although the co-processed FZ cell showed slight long-wavelength improvement, the web cells suffered from severe bulk-lifetime degradation. This could possibly be due to stresses in the web that result in bulk defects when the textured material is subjected to subsequent high-temperature steps. Work on these commercial materials is ongoing and will be reported later.

ASE

Due to series and shunt resistance problems, the textured EFG cell performance did not surpass that of planar EFG cells. We are endeavoring to determine the cause of this problem and will report on this material at a later time.

CONCLUSIONS

Both of the RIE-textured Shell tri-c Si cell groups outperformed the standard planar controls by up to 6%, while wet-textured cells actually performed worse. If tricrystal cells are used in production to increase yields and reduce costs, RIE-texturing should be able to boost their performance.

The BP Solar cells showed a small 1% gain in efficiency without the use of an expensive post-texture RCA clean. This shows potential for the use of RIE-texturing as a replacement for saw-damage removal etching in order to maintain efficiencies when cells are made thinner. This would increase the number of wafers produced per ingot significantly and markedly reduce cell and module costs.

ACKNOWLEDGEMENTS

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